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The climate and health effects of a USA switch from coal to gas electricity generation

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ABSTRACT

Abundant natural gas at low prices has prompted industry and politicians to welcome gas as a ‘bridge fuel’ between today's coal-intensive electric power generation and a future low-carbon grid. We used existing national datasets and publicly available models to investigate the upper limit to the emission benefits of natural gas in the USA power sector. As a limiting case, we analyzed a switch of all USA coal plants to natural gas plants, occurring in 2016. The human health benefits of such a switch are substantial: SO_2 emissions are reduced from the baseline (MATS (Mercury and Air Toxics Standard) retrofits by 2016) by more than 90%, and NO_X emissions by more than 60%, reducing total national annual health damages by \$20 − \$50 billion annually. While the effect on global temperatures is small out to 2040, the USA power plant fleet's contribution could be changed by as much as −50% to +5% depending on the rate of fugitive CH_4 emissions and efficiency of replacement gas plants.

1. Introduction

Over the past decade shale gas development has increased USA domestic gas production by 40% [1]. Abundant gas at low prices has prompted industry and politicians to welcome gas as a ‘bridge fuel’ between today's electric power generation system, whose largest single fuel is coal, and a future, low-carbon grid. Current US policy includes “actions to promote fuel switching from oil and coal to natural gas” [2].

Recently, a growing body of research has questioned the ability of domestic natural gas to substantially reduce USA GHG (greenhouse gas) emissions. Natural gas power plants typically emit 50%–60% less carbon dioxide (CO_2) than coal plants due to their higher efficiency and lower carbon content of their fuel [3]. However, fugitive emissions from the production and transportation of natural gas (methane, CH_4), itself a potent GHG, may diminish these climate benefits [4–9].

The human health consequences of such a shift have not received as extensive discussion as the GHG effects. Compared to coal plants without emission controls, natural gas plants emit less sulfur dioxide (SO_2) and nitrogen oxides (NO_x), precursors of particulate matter. Natural gas also has lower primary emissions of particulate matter up to 2.5 μm in size ($PM_{2.5}$) and particulate matter up to 10 μm in size (PM_{10}) than coal. Exposure to $PM_{2.5}$ has been linked to human mortality and morbidity [10–14]. EPA regulations, including the CAIR (Clean Air Interstate Rule), the CSAPR (Cross-State Air Pollution Rule), and MATS (Mercury and Air Toxics Standard), are designed to reduce these emissions [14–16]. These regulations have been one cause of a switch from coal to natural gas plants [17,1].

We investigated the potential for natural gas to reduce emissions of criteria pollutants and GHGs from the USA electric power sector. To establish an upper bound on the potential benefits, we analyzed a switch of all USA coal plants to natural gas plants, occurring in 2016. We emphasize that we model this instantaneous shift in order to understand the largest potential changes that such a switch from coal to gas could make. We quantified the reductions in total power sector emissions that would occur, as well as the associated climate and health benefits.

Our intent was not to quantify the cost effectiveness of switching to gas nor the optimal generation fleet. Rather, the goal was to identify the limits to achieving U.S. pollution reduction goals through the use of natural gas power generation. This study differs from existing studies of the climate and health implications of U.S. coal plants [4,18,8,19,6], in that we attempted to quantify the maximum achievable benefit of switching the USA fleet of coal

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generators to gas plants. In reality, the switch from coal to gas would take several years, and the pollution reduction benefits would be less than we identify in the thought experiment we present here. We also directly compare the magnitude of the reduction in criteria pollutant emissions to that of GHG emissions.

We used U.S. DOE (Department of Energy) forecasts of emissions and generation as the baseline for our analysis. These forecasts include a significant reduction in SO_2 and NO_X emissions from existing coal plants from 2016 onward due to retrofits to comply with MATS. From this baseline, we replaced all coal plants with natural gas plants, starting in 2016. We then used two publicly available models to compute the health benefits of such a switch: the APEEP (Air Pollution Emission Experiments and Policy) model [20] and the EASIUR (Estimating Air pollution Social Impact Using Regression) model [21,22]. Using the GTP (Global Temperature Potential), we estimated how switching from coal to gas would affect the power plant fleet's contribution to global temperature until 2040, the last year for which EIA (Energy Information Agency) forecasts emissions and generation. We varied the fugitive methane emission rate from 0% to 7%, a range that includes estimates from existing literature [9].

2. Materials and methods

This section describes our research methods. A graphical representation of the model used in this work is given in Appendix A, and a description of metrics is given in Appendix B.

2.1. Calculation of baseline emissions

We developed baseline emission scenarios for 2016–2040 based on the forecasts from the DOE's EIA (Energy Information Agency) [23]. EIA forecasts installed capacity by plant type, electricity generation by fuel type, and total NO_X and SO_2 emissions from the electric power sector. These forecasts include the effects of existing policies, including CSAPR and MATS. We used the EIA's Reference scenario as our analysis baseline; we also consider the EIA's Low Oil and Gas Resource and High Oil and Gas Resource. Descriptions of each scenario are in Appendix C in the Supplementary material. We assumed that any switching from coal to gas not forecast by the EIA would be due to future policies, not market forces.

2.1.1. Baseline NO_X and SO_2 emissions

EIA forecasts total electric power NO_X and SO_2 emissions to 2040. It does not forecast emissions by fuel type. We therefore separated out the NO_X and SO_2 emissions associated with coal, oil, and gas plants. We first calculated NO_X and SO_2 emissions from oil and gas plants. We used plant-level emission data from the EPA AMPD (Air Market Program Database) to identify 2012 capacity-weighted average emission rates for oil and gas plants in 27 eastern states regulated by the EPA CAIR (Clean Air Interstate Rule) [24].

Next, we multiplied these emission rates by EIA's forecast of electricity production to find total NO_X and SO_2 emissions from oil and gas plants. Finally, we calculated coal NO_X and SO_2 emissions as the difference between EIA's forecast of total NO_X and SO_2 emissions and total oil and gas plant emissions.

2.1.2. Baseline $PM_{2.5}$ and PM_{10} emissions

EIA does not forecast direct emissions of $PM_{2.5}$ and PM_{10} from power plants. We assumed that coal and oil plants emit 0.14 kg/MWh of $PM_{2.5}$ and PM_{10}, the limit imposed by the EPA's MATS [15]. Gas plants are not regulated by MATS, and therefore we used data from the 2005 NEI (National Emissions Inventory) [25] and eGRID 2005 [3] to identify gas plant $PM_{2.5}$ and PM_{10} combustion emissions rates. We found the capacity-weighted average emission rate of gas plants in the NEI database to be 0.06 kg/MWh for $PM_{2.5}$ and 0.07 kg/MWh for PM_{10}. For coal, oil and gas plants, we multiplied the assumed emission rates by EIA's forecast of annual electricity generation by each fuel.

2.1.3. Baseline greenhouse gas emissions

EIA does not forecast CO_2 or CH_4 emissions. We calculated CO_2 emissions by multiplying EIA's forecast of total electricity production from each fuel by the 2012 capacity-weighted average CO_2 emission rate of plants of that fuel type. We used plant-level emission data from AMPD to identify 2012 CO_2 emission rates for plants in CAIR states. These generators made up 70% of 2012 CO_2 emissions.

We calculated CH_4 emissions as the sum of combustion emissions and fugitive emissions from CH_4 production and transportation. Combustion CH_4 emissions for each fuel type are the capacity-weighted average CH_4 emission rates of plants in the EPA's eGRID (Emissions & Generation Resource Integrated Database), 2009. We parameterized the rate of fugitive CH_4 emissions in a range of 0–7%, covering estimates from existing literature [9]. We multiplied the fugitive rate by forecasts of total gas to calculate total fugitive CH_4 emissions. Total gas consumed was found by multiplying EIA's forecast of natural gas generation [23] by the capacity-weighted heat rate of existing gas plants in 2012 [3]. Other fugitive emissions (greenhouse gases, NO_x, SO_2, $PM_{2.5}$, PM_{10}) from the production and transportation of coal and natural gas did not qualitatively change our results and were excluded from the analysis. We did not include the coal life cycle emissions because the upstream emissions are only 5% of total GHG emissions of 96 g CO_2e/MJ, four times less than the overall uncertainty of the mean value [6].

2.2. Calculation of replacement plant emission rates

We modeled two scenarios to investigate the benefits of switching from coal to other fuels.

Scenario a) retired all coal plants and built new, high-efficiency NGCC (natural gas combined cycle) plants. New NGCC plants were assumed to have a heat rate of 5700 Btu/MWh achieved by state-of-the-art GE Flex-60 and Siemens Frame-H [26,27]. The CO_2 emission rate was calculated by multiplying the heat rate by the carbon content of natural gas. Other emission rates were assumed to be the load-weighted average emission rates of 450 existing NGCC plants, as identified by the EPA's National Electric Energy Data System [28]. This assumption somewhat overstates emission rates, as emission rates of new, high-efficiency NGCC will likely be lower than the existing NGCC fleet average. NO_X and SO_2 emission rates were based on 2012 emission rates (AMPD); CH_4 emission rates were from eGRID 2009; $PM_{2.5}$ and PM_{10} emission rates were based on NEI 2005.

Scenario b) retired all coal plants and built new natural gas plants with same heat rate and emission rates as the existing gas fleet's load-weighted average, considering both NGCC and combustion turbine plants. Heat rates, CO_2, NO_X and SO_2 emission rates were based on 2012 data (AMPD); CH_4 emission rates were from eGRID 2009; $PM_{2.5}$ and PM_{10} emission rates were based on NEI 2005. This scenario isolates the benefits of fuel switching from the benefits of switching to high-efficiency plants (scenario a). Load-weighted emission rates and load weighted heat rates were calculated as described in the Supplemental material.

In addition to these two scenarios, we also modeled a scenario in which coal plants were replaced by new plants that have zero emissions of all pollutants, either renewable or nuclear plants. Associated results can be found in the Supplementary material,

Appendix C, Figures C.1 – C.4. We assumed the replacement plants could provide firm baseload power; in reality, variable renewables such as wind would need storage to serve as baseload.

We assumed replacement plants are built at the same location and have the same capacity as the coal plants they replace. We believe that this assumption is reasonable, as the sites will have much of the infrastructure needed for new plants, such as access to transmission. Our analysis ignored changes in the dispatch order that may occur due to fuel switching, or changes in load due to consumer price response.

2.3. Calculation of health effects

Many health models exist [29,18] and have been used by the EPA as technical support for major pollution regulations [14]. In this study, we used two publicly available models: the APEEP (Air Pollution Emission Experiments and Policy) model [20] and the EASIUR (Estimating Air pollution Social Impact Using Regression) model [22]. We used these models to monetize the benefit to human health and the environment caused by changes in emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10}. We excluded damages due to VOCs (volatile organic compounds) and ammonia (NH_3) from our analysis due to uncertainty in the atmospheric science surrounding these pollutants, and the relatively small damages they cause compared to SO_2, NO_X, and PM [30,31].

APEEP uses a reduced form air transport model and linear dose–response function to monetize the damages to human health and the environment caused by a marginal ton of emissions of NO_X, SO_2, $PM_{2.5}$, PM_{10}, VOCs, and NH_3 from each county in the USA. Health effects, if valued at \$6 million per statistical life, constitute 94% of the total APEEP damages, dominating environment damages (visibility loss, damages to forestry and agriculture, damage to manmade structures) [20]. Compared to US EPA, APEEP underestimates damages [20].

EASIUR [21,22] was derived using regression on a large dataset created by CAMx, a state-of-the-art chemical transport model [32]. EASIUR closely reproduces the social costs of emissions predicted by full CAMx simulations but without the high computational costs. The EASIUR's social costs are derived only on the basis of the effect of ambient $PM_{2.5}$ on mortality, which usually accounts for more than 90% of social costs. It estimates the monetized effects of $PM_{2.5}$ from emissions of EC (elemental carbon), SO_2, NO_x, and NH_3 affecting over a large area downwind (up to about two thousand kilometers).

Because both models calculate emissions' damages as a function of location, we estimated individual coal plant emissions in the continental United States of SO_2, NO_X, $PM_{2.5}$, and PM_{10}. Although EIA forecasts total NO_X and SO_2 emissions, plant-level emissions out to 2040 are highly uncertain. We assumed the fraction of total coal SO_2 and NO_X emissions from each plant remains constant from 2012 levels through 2040 [3]. We assumed each coal plant emits 0.14 kg/MWh of $PM_{2.5}$ and PM_{10} [15].

Switching all coal plants to gas would have a significant effect on criteria pollutants, and it might be argued that both models' baseline emissions are affected enough so that the human health effects are no longer good estimates. However, there is good evidence that the formation of $PM_{2.5}$ caused by SO_2 and NO_X is linear with reduced emissions, with no threshold [33]. Major cohort studies have found $PM_{2.5}$ concentration-response functions and mortality are linear with no threshold [34–36]. Since we find NO_X accounted for only 8% of total health damages from the electricity sector in 2012, we ignore the known second-order nonlinearities in $PM_{2.5}$ formation associated with NO_X emissions due to decreasing SO_2 emissions.

2.4. Calculation of climate effects

We calculated resulting temperature changes using a metric used by the IPCC, *GTP* (Global Temperature Potential) [37,38]. GTP is defined as the ratio between the global mean surface temperature change (ΔT) at a given future *TH* (time horizon) following an emission (pulse or sustained) of a compound *x* relative to an equivalent mass of CO_2 *(36)*, or:

$$GTP_x^{TH} = \frac{\Delta T_x^{TH}}{\Delta T_{CO2}^{TH}} \tag{1}$$

Since power plant emissions are typically given at annual intervals, the total change in temperature (ΔT) due to emissions of all pollutant types (x) [38] over the entire *TH* (time horizon) years can be approximated as:

$$\Delta T = \sum_{x=1}^{X} \sum_{t=1}^{TH} GTP_x(t) * \Delta T_{CO_2}(t) * M_x(t) \tag{2}$$

where *M* is the mass of the pollutant *x* emitted in year *t* (kg) and ΔT_{CO2} is the temperature response in year *n* due to a 1 kg pulse emission of pollutant emitted in year 0 (K/kg). Common time horizons chosen include $n = 20$ (the total temperature change 20 years in the future) and $n = 100$ (the total temperature change 100 years in the future).

For the results shown in this paper, we calculate the temperature forcing due to carbon dioxide and methane. GTP_{CO2} is defined to be 1, and ΔT_{CO2} can be represented through empirical analysis [39]. Fossil methane, including climate change feedbacks, is estimated to have a GTP at 20 years (GTP20) of 68, and a GTP100 of 15, although estimates are highly uncertain (roughly ± 75%); the most recent IPCC report fully characterizes GTP_{CH4}^{TH} over a century [39]. A discussion of the global warming potential of CO_2 and CH_4 emissions can be found in Appendix B in the Supplementary material.

While this simple model can allow the user to intuitively understand the changes in CO_2 and CH_4, it does not take into account the effects of NO_x, SO_x, BC (black carbon), and OC (organic carbon). Previous literature has shown that a shift from coal to gas would significantly reduce SO_2, offsetting both the climate forcing from the reduction in black carbon and some of the GHGs [7]. However, this literature also assumes the base coal fleet emits a large amount of SO_2, whereas in our analysis, the baseline forecasts of SO_2 emissions account for mandated SO_2 emissions due to the MATS standard, and therefore already have low SO_2 emissions. Thus, we do not expect to see large temperature changes from NO_x, SO_x, or BC.

To confirm this, we modeled climate change effects from NO_X, SO_x, and BC using a chemistry model within the publicly available MAGICC6 model [40] a simple/reduced complexity climate model including an ocean, an atmosphere, a carbon cycle, and indirect aerosol effects; Appendix D in the Supplementary material contains a full model description and validation tests.

Table 1
2016 load-weighted average emission rates for USA coal plants in EIA Reference Case, and replacement plants for scenarios a) and b).

Plant type	Combustion emission rates (kg/MWh)					
	CO_2	NO_x	SO_2	CH_4	$PM_{2.5}$	PM_{10}
Coal – 2016	910	0.69	0.72	0.01	0.14	0.14
Scenario a): High-efficiency gas	300	0.09	0.02	0.008	0.06	0.07
Scenario b): Average gas	450	0.17	0.02	0.009	0.06	0.07

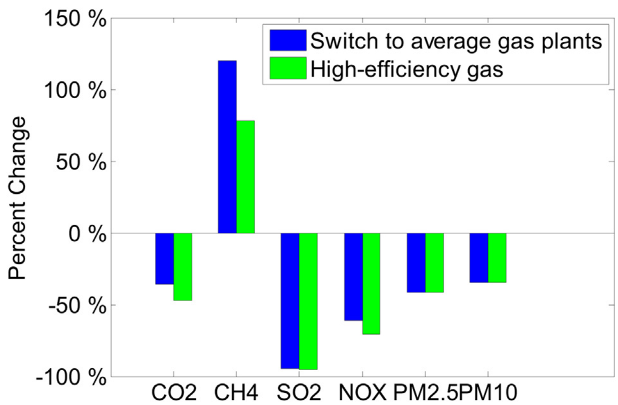

Fig. 1. Effect of coal-to-gas switching as a percent change in total USA electric power GHG emissions (CO_2 and CH_4, the latter using a 3% fugitive CH_4 rate), and criteria pollutants from the EIA Reference Case in 2025. Reductions are constant across years 2016–2040.

3. Results

Table 1 shows the load-weighted average emission rates and heat rates of coal plants in 2012, as well as the emission rates and heat rates for the coal replacement plants in scenarios a) and b). Switching to average gas reduces CO_2 emissions by half; switching to high-efficiency gas reduces CO_2 emissions by $^2/_3$. Both average and high-efficiency gas plants emit an order of magnitude less SO_2 and NO_X than coal plants.

3.1. Change in emissions

Fig. 1 shows emission reductions due to switching from coal to gas. The switch reduces SO_2 emissions by more than 90%, NO_X emissions by more than 60%, and PM emissions by 40% from the EIA's reference case (Appendix C, Figures C.8 – C.11 in the Supplementary material). Annual electric power CO_2 emissions are reduced by 35%–47%; CH_4 emissions would increase by 80%–120%, assuming a 3% fugitive CH_4 emission rate. Because coal plants are the primary source of criteria pollutant emissions, switching from coal has a larger effect on criteria pollutant emissions than GHG emissions. Table 2 shows that CH_4 reductions are highly sensitive to the assumed fugitive CH_4 emission rate. Emission reductions are similar for the EIA Reference Case, High Gas Resource Case, and Low Gas Resource Case (see Appendix C in the Supplementary material).

3.2. Effect on human health

Switching from coal to gas would significantly reduce SO_2, NO_X, and PM emissions (Fig. 1). The monetized annual health and environmental damages of emissions, via the APEEP and EASIUR models, are shown in Fig. 2. We find that when considering a switch to either high-efficiency gas or average gas plants, publicly available models provide a large range in damage reductions estimates; damage reductions are $20 billion - $24 billion per year (via APEEP) and $40–50 billion per year (via EASIUR). Both models show damage reductions increase from 2016 to 2025, as the EIA forecasts increasing coal generation over that time period. More than 75% of damage reductions are due to reductions in SO_2; reductions in NO_X and $PM_{2.5}$ each make up 10% of damage reductions. Health and environmental damages vary regionally (Fig. 3). Most damages occur in the Ohio River Valley and Southeast due to the high concentration of coal plants and significant downwind population.

3.3. Effect on atmospheric concentrations of GHG emissions

In agreement with published literature, using the simple GTP model we find that climate benefits for a USA policy of switching from coal to natural gas are limited unless this action results in

Table 2
Sensitivity of CH_4 emissions in 2025 to fugitive CH_4 emission rate, EIA Reference Case.

Scenario	Percent change in CH_4 emissions			
	0% fugitive CH_4	3% fugitive CH_4	5% fugitive CH_4	7% fugitive CH_4
Baseline	0	8	13	18
A) Switch to high-efficiency gas	0	14	23	33
B) Switch to average gas	0	17	29	40

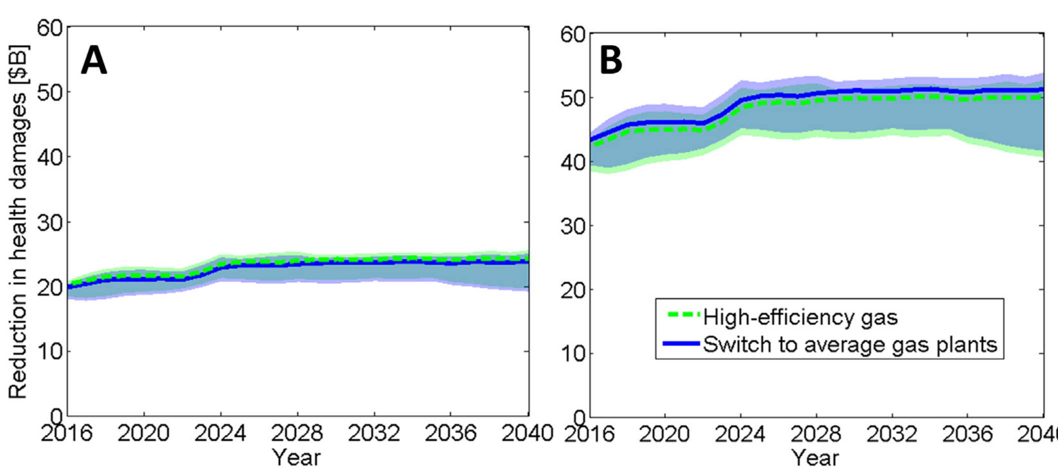

Fig. 2. Reduction in annual health damages due to switching from coal, using a $6 million value of statistical life. Solid line is EIA reference case; shaded area is the range across EIA reference case, high gas resource case, and low gas resource case. A: APEEP results; B: EASIUR results.

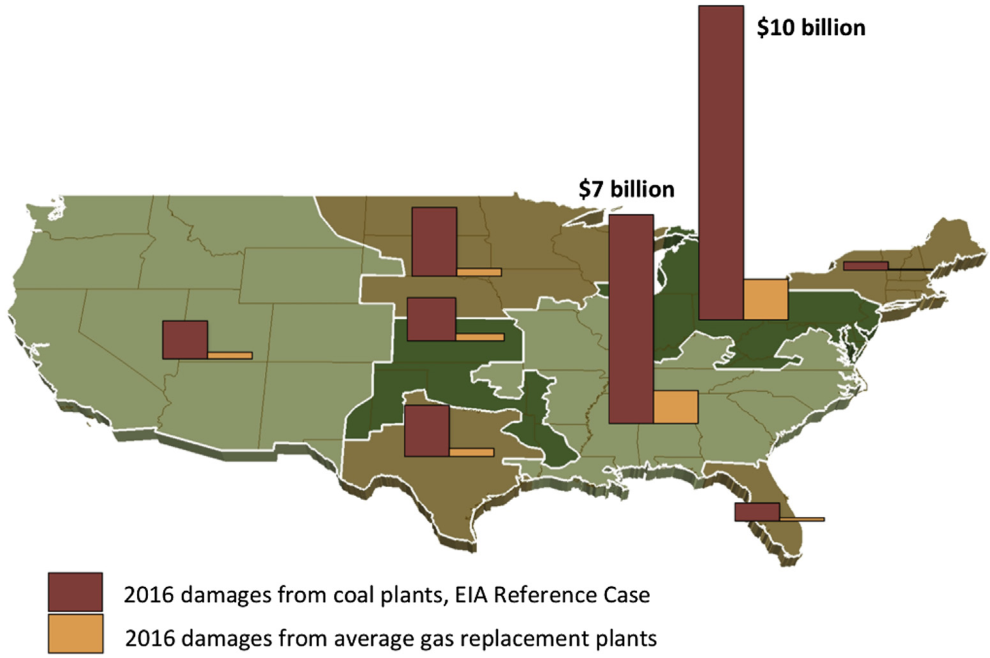

Fig. 3. 2016 annual health and environmental damages due to emissions of criteria pollutants from coal plants, by NERC region, using the APEEP model. Replacing coal plants with average gas plants (scenario b) reduces damages most significantly in the Midwest and Southeast.

other major polluters reducing their GHG emissions. Figs. 4 and 5 show the change in temperature from business as usual minus the change in temperature for the two scenarios. Switching from coal to natural gas results in a difference of temperature change between −0.02 °C and +0.03 °C, depending on the assumed fugitive CH_4 rate. Differences in temperature changes are insensitive to the baseline EIA case assumed. As shown in the Appendix D in the Supplementary material, the MAGICC6 model simulates a nearly identical contribution of CO_2 and CH_4 to temperature.

While a small change to global temperatures, these changes are a significant change to the temperature contributions from the US power plant fleet. Table 3 shows the fraction of change in temperature from scenarios a) and b) divided by the change in temperature from business as usual (EIA Reference Case). The table shows results for a $GTP20_{CH4}$ of 68, as well as the $GTP20_{CH4}$ uncertainty range of ±75%. Assuming $GTP20_{CH4}$ is 68, we find that a switch to an average gas plant can change the power plant fleet's contribution to temperatures in 2040 by −40% to +30%, depending on fugitive emissions rate. A switch to clean plants can change the power plant fleet's contribution to temperatures by −50% to +5%. Results are insensitive to the baseline EIA case assumed.

Appendix D in the Supplementary material contains an analysis of the effects of SO_X, NO_X, BC, and OC on warming through 2100 using the publicly available MAGICC6 model. None of these cause large climate change effects; SO_2 due to the greatly lowered

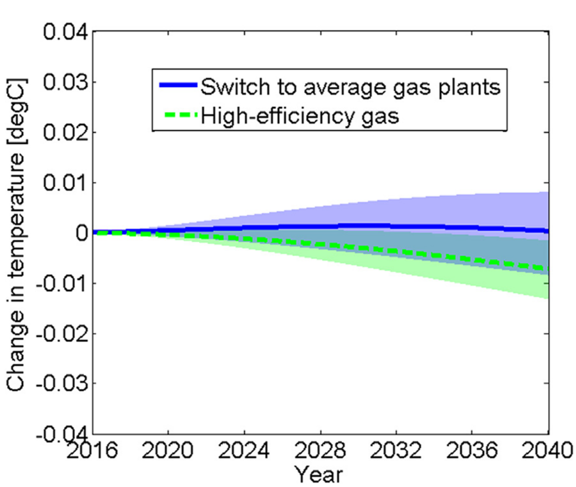

Fig. 4. Change in temperature from scenarios (A) high-efficiency gas and (B) average gas minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is range across EIA reference case, high gas resource case, and low gas resource case. Assumed $GTP20_{CH4}$ of 68 ± 75%.

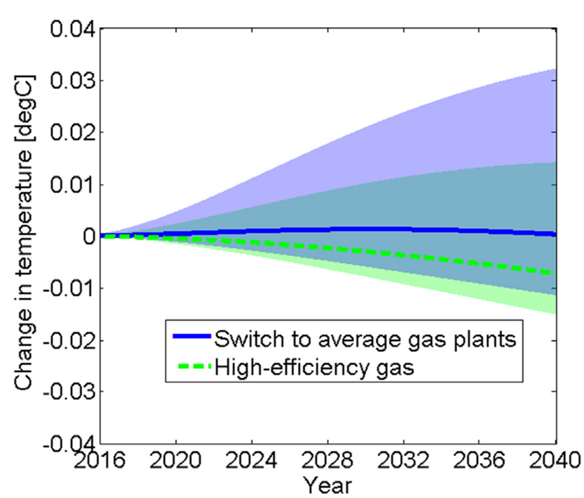

Fig. 5. Effect of fugitive CH_4 rate uncertainty. Change in temperature from scenarios (A) high-efficiency gas and (B) average gas minus change in temperature from business as usual. Temperature changes include contributions from CO_2 and CH_4 only. Solid line is 3% fugitive CH_4 rate for the EIA reference case; shaded area is represents uncertainty across EIA reference case, high gas resource case, and low gas resource case and 0%–7% fugitive CH_4 rate. Assumed $GTP20_{CH4}$ of 68 ± 75%.

Table 3
Fraction of change in temperature in 2040 from scenarios (A) high-efficiency gas and (B) average gas plants divided by the change in temperature from baseline EIA reference case. Temperature changes include contributions from CO_2 and CH_4 only. Reductions are constant across 2016–2040. Assumed $GTP20_{CH4}$ of 68; uncertainty range of ±75% in parenthesis.

Scenario	Change in warming contributed by U.S. electric power sector, 2040			
	0% fugitive CH_4	3% fugitive CH_4	5% fugitive CH_4	7% fugitive CH_4
A) Switch to high-efficiency gas	**−47%**	**−18%** (−38%, −3%)	**−5%** (−33%, +11%)	+**5%** (−28%, +21%)
B) Switch to average gas	**−35%**	+**1%** (−24%, +18%)	+**16%** (−18% + 36%)	+**28%** (−12%, +49%)

emissions in order to meet the MATS standards, NO_x because it is a very weak climate change forcer, and BC because newer literature has shown that the amount of BC from coal power plants is much less than previously expected [41,42].

4. Conclusions

Human health in the United States can greatly benefit from policies that continue the reduction of criteria pollutant emissions from coal plants, by switching to gas, installing emissions controls, or switching to renewables or nuclear. Switching to gas would greatly reduce criteria pollutant emissions; SO_2 emissions would be reduced by more than 90%. Annual health damages could be reduced further by \$20 – \$50 billion if coal plants are either replaced with gas plants or fitted with flue gas desulfurization emission controls.

In the short term, the potential for natural gas to reduce the USA power sector's contribution to global warming is highly sensitive to the CH_4 fugitive rate and efficiency of gas plant installed. Assuming 3% fugitive CH_4 emissions, switching all coal plants to high efficiency NGCC plants would reduce the power sector's contribution to warming by 20% in 2040. Assuming $GTP20_{CH4}$ of 68, a switch to high-efficiency NGCC plants can change the power sector's contribution to warming changes by −50% to +5% for fugitive CH_4 rates of 0%–7%. Switching to average-efficiency plants can change warming contribution by −35% to +30% for fugitive rates of 0%–7%. Considering the uncertainty in $GTP20_{CH4}$ estimates further increases the uncertainty in our results. In all cases, the net effect on global temperatures by 2040 is inconsequential unless US leadership induces pollution control by other large nations.

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Appendix. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.03.078.

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